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Carbon emissions from energy consumption in China: Its measurement and driving factors

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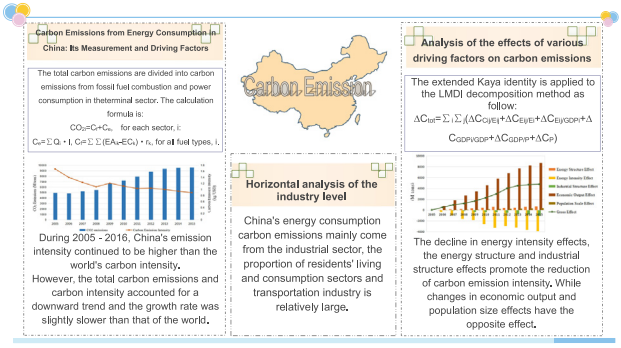
HIGHLIGHTS

- Economic output increase is the largest driving factor promoting the CO_2 emissions of China.
- In China, CO_2 missions from energy consumption in industrial sector accounted for the greatest proportion.
- Phasing out excess capacity in China reduced emissions in the industry sector.
- Energy intensity reduction is a key for high-energy-consuming countries to reduce CO_2 emissions.
- Promoting the transformation of the industrial structure is an efficient way to reduce CO_2 emissions.

GRAPHICAL ABSTRACT


Carbon Emissions from Energy Consumption in China: Its Measurement and Driving Factors
The total carbon emissions are divided into carbon emissions from fossil fuel combustion and power consumption in theterminal sector. The calculation formula is:
Carbon Emission
Analysis of the effects of various driving factors on carbon emissions
The extended Kaya identity is applied to the LMDI decomposition method as follow:
During 2005 - 2016, China's emission intensity continued to be higher than the world's carbon intensity. However, the total carbon emissions and carbon intensity accounted for a downward trend and the growth rate was slightly slower than that of the world.
Horizontal analysis of the industry level
China's energy consumption carbon emissions mainly come from the industrial sector, the proportion of residents' living and consumption sectors and transportation industry is relatively large.
The decline in energy intensity effects, the energy structure and industrial structure effects promote the reduction of carbon emission intensity. While changes in economic output and population size effects have the opposite effect.

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ABSTRACT

To address climate change effectively, it is essential to quantify CO_2 emissions and the driving factors in high-energy-consuming countries. China is the top CO_2-emitting country; moreover, there is a lack of comprehensive analytical studies on quantifying the contributions of key drivers to high-energy-consuming countries' CO_2 emissions. Therefore, based on data of China's energy consumption from 2005 to 2016, this paper combines the extended Kaya identity with the logarithmic mean Divisia index (LMDI) decomposition method to construct an optimized carbon emission decomposition model. Carbon emission and carbon emission intensity are measured and decomposed. Then, the results of the decomposition are discussed, and the effects of various drivers on carbon emissions from energy consumption in China are analysed. Furthermore, we demonstrate real applications of decomposition analysis in policy-making using examples from China and present some ideas to reduce CO_2. The results show that from 2005 to 2016, China's total carbon emissions accounted for nearly one-third of the world's total carbon emissions, and the intensity of carbon emissions in China was generally higher than that of worldwide. The rapid development of economy and acceleration of urbanization are not conducive to reduction of carbon emissions. Reducing the intensity of energy consumption, adjusting the internal structure of the industry and perfecting the economic policy system should be important means used to promote the development of China's low-carbon economy in the future.

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1. Introduction

According to the "Global Greenhouse Gas Bulletin" issued by the World Meteorological Organization on October 30, 2017, the concentration of CO_2 in the air rose at an alarmingly rapid rate in 2016, reaching the highest level in the past 800,000 years, which made the global atmosphere in danger. Therefore, methods to reduce CO_2 emissions and achieve a low-carbon economy have become significant topics worldwide. The key lies in measuring CO_2 emissions from energy consumption and studying the factors influencing carbon emissions. Given the characteristics of "rich coal, lacking oil and gas", China has become the world's largest energy consumer, the largest oil importer and the second largest liquid natural gas (LNG) importer. According to the International Energy Agency (IEA), in 2017, annual CO_2 emissions of global fossil fuels have increased to 36.3 billion tons, and about one-third came from China. To slow down the increase in carbon emissions, China proposed a reduction of its CO_2 emissions per unit gross domestic product (GDP) by 60–65% in 2030 (in comparison with the emissions in 2005), under the framework of the Paris Agreement; meanwhile, a carbon emissions peak will be achieved. This is not only China's strong commitment to the international community but also an inevitable choice for China to achieve sustainable development. On the other hand, as the largest developing country, China's economic development will have a structural impact on the world political and economic pattern. At present, with the increase in domestic consumption and the development of energy-intensive industries, China is facing enormous pressure to reduce its CO_2 emissions. Therefore, it is necessary to measure carbon emissions from energy consumption in China and determine its driving factors, which are of great significance to promote the process of CO_2 emission reduction in China and worldwide in the future (Fig. 1).

Currently, in the study of energy consumption, there are two general decomposition methods used worldwide on measurements of carbon emissions to determine its influencing factors: One method is the structural decomposition approach (SDA). SDA was first proposed by Indian scholar Debesh (2006) in 2006 to solve the input-output structural decomposition problem. Later, Shang and Jiang (2009) introduced SDA to the decomposition of China's energy consumption structure. Subsequently, SDA has been widely used in the structural decomposition and analysis of carbon emissions in China (e.g., Wang et al., 2012; Xu et al., 2012; Duan and Yang, 2017). SDA is based on input-output tables and requires input-output data. However, China generally compiles input-output tables every five years, which is a long time span and is not conducive to in-depth research. Therefore, a second method, known as the index decomposition approach (IDA), is generally adopted. IDA is based on departmental summation data and is suitable for time-series analysis. In addition, IDA is more feasible for practical applications. The logarithmic mean Divisia index (LMDI) decomposition method based on IDA was first proposed in 2004 and introduced to the decomposition of energy consumption (Ang, 2004). This method can decompose multiple factors, and the decomposed result also solves the problem of residual items, data zeros and negatives. Therefore, it is widely used in the establishment and analysis of the CO_2 emissions driver decomposition model. Based on the LMDI decomposition method, the measurement of CO_2 emissions and their influencing factors can be studied at national, provincial, municipal, regional and industry levels. Xu et al. (2012), Fan (2013) and Chong et al. (2015) used the LMDI method to decompose and analyze the driving factors of carbon emissions due to China's energy consumption. Regarding China's carbon emissions, the contribution rate from economic output is the greatest. Ramachandra and Shwetmala (2012) analysed the relationship between India's high level of energy consumption and lower per capita emissions. And it showed that low energy efficiency and weak policies were the main factors of increasing total emissions; Brizga et al. (2013) analysed the effect of energy intensity, energy mix, and population on CO_2 emissions in the former Soviet Union from 1990 to 2010. The results show that these factors play different roles during different stages of economic development. Alam et al. (2016) discussed the effects of income, energy consumption and population growth on CO_2 emissions in India, Indonesia, China and Brazil during 1970–2012 but failed to quantify the driving factors. Additionally, some scholars have combined the LMDI with the spatial autocorrelation method, Cobb-Douglas production function or other techniques to study energy consumption in China (Cheng et al., 2013; Wang et al., 2014). Some other scholars applied the LMDI to the European Union, Iran, Middle Eastern countries and countries along the Belt and Road to track and decompose their CO_2 emissions (González et al., 2014; Mousavi et al., 2017; Guo et al., 2018). With the development of regional economies, the LMDI has been applied to the study of carbon emissions at the provincial and municipal levels and the decomposition analysis of the influencing factors (e.g., Peng and Wu, 2012; Tian et al., 2015; Carmona and Collado, 2016; and Chong et al., 2017). Due to the development of economy and the refinement of industrial division, an increasing number of scholars are no longer confined to longitudinal research at the regional level, but instead focus on the industry department: Jeong and Kim (2013), Pan et al. (2011), Dai et al. (2015) and Li et al. (2016) applied the LMDI method to measure carbon emissions from South Korea's industry, China's manufacturing and agriculture

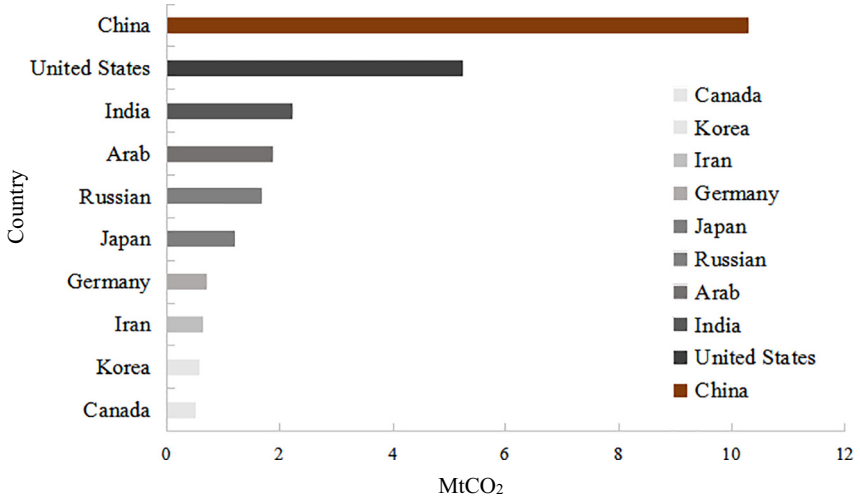

Fig. 1. Ten countries with the highest carbon emissions in 2014.
*Data source: the World Bank (http://www.worldbank.org/).

industries, and the agricultural energy consumption of 18 European countries. They found that decreasing energy intensity is the main factor behind decreasing CO_2 emissions. Feng and Wang (2015) and Song et al. (2018) decomposed and analysed the driving factors of carbon emissions within both China's provinces and its construction industry, while Zhang (2016) analysed China's energy consumption from the perspective of the logistics industry.

Overall, although relevant global studies on carbon emissions from energy consumption are becoming increasingly in-depth, and the analytical methods are rapidly improving, there are still some deficiencies in the following aspects (1) Most of the literatures have only studied the industrial sector and did not consider residential consumer spending. However, the residential consumer sector has become an important contributor to carbon emissions from energy consumption and should not be ignored. (2) Some literatures have mixed up coal data and raw coal data when studying carbon emissions from energy consumption. However, in energy statistics, coal data include raw coal data, and in the calculation of carbon emissions, relevant literatures only provide calculation coefficients for raw coal. Therefore, the use of coal data will cause some differences in data collection and calculation, which in turn will lead to errors in analysis. (3) Such studies are absent or imperfect in high-energy-consuming countries such as India, Brazil and China, however, these high-energy-consuming countries are the major contributors to the global carbon emissions. Thus, causes of carbon emissions from energy consumption need to be further studied. Therefore, it is necessary to establish a more comprehensive and scientific decomposition model of factors affecting carbon emissions to conduct in-depth research on such issues.

Taking China as an example, this paper focuses on carbon emissions from the consumption of nine major sources of energy (raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas and electricity) in seven consumer sectors (agriculture, industry, construction, transportation, retail and accommodations, other industries and the residential consumption sector). First, we calculate the carbon emissions from energy consumption in China from 2005 to 2016. Then, Kaya-LMDI decomposition model is established to analyze the main driving factors (i.e., energy structure, energy intensity, industrial structure, economic output, and population scale) of CO_2 emissions from energy consumption in China. The decomposition results of each driving factor are discussed. Furthermore, the policy recommendations for carbon emission reduction are presented to consider the discussed results and the current development situation in China. Therefore, the present study is a case of international significance due to (1) the influential role of China in world energy consumption; (2) the absence of this type of study in high-energy-consuming developing countries worldwide; and (3) the quantification of the driving factors of CO_2 emissions to meet global climate targets. This work is not only of great theoretical significance for other high-energy-consuming developing countries, but also of practical significance for future development and construction worldwide.

2. Methods and data sources

2.1. Carbon emissions-related calculation methods

The "*Guidelines for National Greenhouse Gas Inventories*" stipulates that provincial-level CO_2 emissions from energy activities can be measured by Intergovernmental Panel on Climate Change (IPCC) method 1: total carbon emissions are divided into carbon emissions from fossil fuel combustion and carbon emissions from end user electricity consumption (IPCC, 2006). The formula is

$$C = C_f + C_e \tag{1}$$

where C represents the total carbon emissions, C_f represents carbon emissions from combustion of fossil fuels, and C_e represents the end user CO_2 emissions from electricity consumption.

CO_2 emissions from fossil fuel combustion is based on a comprehensive summation of the apparent consumption of various fossil fuels, the unit calorific value and the carbon content of various fuel types, the average oxidation rate of major equipment used for burning various fuels, and deduction of non-energy uses of fossil fuels, such as carbon sequestration. The formula is

$$C_f = \sum_{i=1}^{7}\sum_{k=1}^{9}(E_{Aik} - E_{Ck}) \cdot A_k \cdot C_{Qk} \cdot O_k \cdot \frac{44}{12} = \sum_{i=1}^{7}\sum_{k=1}^{9}(E_{Aik} - E_{Ck}) \cdot \rho_k \tag{2}$$

where E_{Aik} represents the apparent consumption of the kth fossil fuel in the ith industry sector (unit: t, m^3, or kW·h). E_{Ck} represents carbon sequestration in the kth energy source (unit: t, or m^3). A_k represents the average low caloric value of the kth energy source (unit: GJ/t or GJ/m^3). C_{Qk} represents the calorific value of carbon in units representing the kth energy source (unit: tC/TJ). O_k represents the carbon oxidation rate in the process of fossil fuel combustion (unit: %), and ρ_k represents the CO_2 emission factor of the kth fossil fuel (unit: tCO_2/t or tCO_2/m^3).

Carbon emissions generated by consumption of electricity by regional terminal departments are equal to the sum of the electricity used by the end-users of various industries and the CO_2 emission factors, annually. The formula is

$$Ce = \sum_{i=1}^{7} Q_i \cdot \lambda \tag{3}$$

where Q_i represents the end user power consumption in the ith industry sector and λ represents the average CO_2 emission factor of the grid in the region annually.

2.2. Data sources

The fossil fuel energy consumption data in this paper come from "*China Energy Statistical Yearbook (2005-2016)*". The power energy consumption data come from the terminal consumption in the physical quantity balance table. The average CO_2 emissions factor of the regional power grid is taken from the "*China Regional Grid Baseline Emission Factor in 2007*", "*China Regional Grid Baseline Emission Factor in 2010*", "*China Regional Grid Baseline Emission Factor in 2012*", "*China Regional Grid Baseline Emission Factor in 2015*" and "*China Regional Grid Baseline Emission Factor in 2017*". The correlation coefficient of natural gas is the average of the upper and lower limits of the interval. The data and sources of various energy-related calculation coefficients are shown in Table 1.

2.3. Decomposition model

2.3.1. Kaya identities based on the carbon emission decomposition model

Kaya identity, which was first proposed by the Japanese scholar Kaya Yoichi (1989), has been widely adopted in studies, including those of well-known institutions, such as the IEA, to solve the problem of factors decomposition of greenhouse gas emissions. The formula is

$$GHG = \frac{GHG}{TOE} \cdot \frac{TOE}{\mathrm{GDP}} \cdot \frac{\mathrm{GDP}}{POP} \cdot POP = f \cdot e \cdot g \cdot P \tag{4}$$

where *GHG*, *TOE*, GDP and *POP* represent the total greenhouse gas emissions, primary energy consumption, gross domestic product, and total population of the country, respectively. The three ratios on the right-hand side of the equation (*GHG*/*TOE*, *POE*/GDP, and GDP/*POP*) represent the energy intensity (f), energy intensity per unit of GDP (e), and per capita GDP (g), respectively. These three factors and the total population constitute the four drivers of carbon emissions.

Table 1
Calculation coefficients of various energy sources.

	Average low calorific value GJ/t	Standard coal factor tce/t	Carbon content per unit calorific value tC/TJ	Carbon oxidation rate %	CO_2 emission factor tCO_2/t
Raw coal	20,908	0.7143	26.37	0.94	1.9003
Coke	28,435	0.9714	29.5	0.93	2.8604
Crude oil	41,816	1.4286	20.1	0.98	3.0202
Gasoline	43,070	1.4714	18.9	0.98	2.9251
Kerosene	43,070	1.4714	19.5	0.98	3.0179
Diesel oil	42,652	1.4571	20.2	0.98	3.0959
Fuel oil	41,816	1.4286	21.1	0.98	3.1705
Nature gas	32,238–38,931 GJ/m^3	1.1000–1.3300	15.3	0.99	1.7904–2.1622 $kgCO_2/m^3$
Electricity	3600 KJ/KW h	0.1229	/	/	/

Notice: (a) An average low calorific value equal to 29,307 kJ is called 1 kg of coal equivalent (1 kgce). (b) The data in the first three columns are from the "*China Statistical Yearbook*" (2016). (3) The data in the fourth and fifth columns are from the "*Guidelines for National Greenhouse Gas Inventories*".

To better analyze the drivers of CO_2 emissions from an energy and sectoral perspective, this paper extends the Kaya identity to the following formula (Johan et al., 2002):

$$C = \sum_i \sum_j \frac{C_{ij}}{E_{ij}} \cdot \frac{E_{ij}}{E_i} \cdot \frac{E_i}{GDP_i} \cdot \frac{GDP_i}{GDP} \cdot \frac{GDP}{P} \cdot P \tag{5}$$

where C represents the total carbon emissions, C_{ij} represents the amount of carbon emissions that the ith sector generates when it consumes the jth energy source, E_{ij} represents the consumption of the jth energy source by the ith sector, E_i represents the total energy consumption of the ith sector, i represents the industry added value of the ith sector, GDP represents the total added value of China's economy, and P represents the total population of China. C_{ij}/E_{ij}, E_{ij}/E_i, E_i/GDP_i, GDP_i/GDP, GDP/P, and P on the right-hand side of the equation above represent the carbon emission factors, energy structure, energy intensity, industrial structure, economic output and population scale, respectively.

2.3.2. Decomposition model of carbon emissions factors based on Kaya-LMDI

To study the contributions of various drivers of CO_2 emissions, this paper applies the extended Kaya identity to the LMDI decomposition method and decomposes the drivers of CO_2 emissions to discuss their contributions. This paper selects the additive decomposition approach of the LMDI decomposition method. The method, based on formula (4), decomposes carbon emissions as follows:

$$\Delta C_{tot} = \sum_i \sum_j \left(\Delta C_{C_{ij}/E_{ij}} + \Delta C_{E_{ij}/E_i} + \Delta C_{E_i/GDP_i} + \Delta C_{GDP_i/GDP} + \Delta C_{GDP/P} + \Delta C_P\right) \tag{6}$$

where ΔC_{tot} represents the total effect of carbon emissions decomposition, $\Delta C_{Cij/Eij}$ represents the effect of carbon emission factors, $\Delta C_{Eij/Ei}$ represents energy structure effects, $\Delta C_{Eij/GDPi}$ represents the energy intensity effect of the industry, $\Delta C_{GDPi/GDP}$ represents the industrial structure effects, $\Delta C_{GDP/P}$ represents the effect of economic output, and ΔC_P represents the population scale effect. The decomposition results of the effects obtained from the Kaya-LMDI decomposition model are as follows:

$$\Delta C_{C_{ij}/E_{ij}} = L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) \cdot \ln \frac{(C_{ij}/E_{ij})^{(t)}}{(C_{ij}/E_{ij})^{(0)}} \tag{7}$$

$$\Delta C_{E_{ij}/E_i} = L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) \cdot \ln \frac{(E_{ij}/E_i)^{(t)}}{(E_{ij}/E_i)^{(0)}} \tag{8}$$

$$\Delta C_{Eij/GDPi} = L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) \cdot \ln \frac{(E_i/GDP_i)^{(t)}}{(E_i/GDP_i)^{(0)}} \tag{9}$$

$$\Delta C_{GDP_i/GDP} = L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) \cdot \ln \frac{(GDP_i/GDP)^{(t)}}{(GDP_i/GDP)^{(0)}} \tag{10}$$

$$\Delta C_{GDP/P} = L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) \cdot \ln \frac{(GDP/P)^{(t)}}{(GDP/P)^{(0)}} \tag{11}$$

$$\Delta C_P = L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) \cdot \ln \frac{P^{(t)}}{P^{(0)}} \tag{12}$$

Among them, for $L(C_{ij}(t), C_{ij}(0))$ in formulas (7)–(12), the following definition are provided:

$$L\left(C_{ij}^{(t)}, C_{ij}^{(0)}\right) = \begin{cases} \left(C_{ij}^{(t)} - C_{ij}^{(0)}\right) / \ln C_{ij}^{(t)} - \ln C_{ij}^{(0)}, & C_{ij}^{(t)} \neq C_{ij}^{(0)} \\ C_{ij}^{(t)}, & C_{ij}^{(t)} = C_{ij}^{(0)} \neq 0 \end{cases} \tag{13}$$

Since carbon emission factors of various energy sources are fixed and the carbon emission factor effect is always zero, formula (6) can be simplified as

$$\Delta C_{tot} = \sum_i \sum_j \left(\Delta C_{E_{ij}/E_i} + \Delta C_{E_i/GDP_i} + \Delta C_{GDP_i/GDP} + \Delta C_{GDP/P} + \Delta C_P\right) \tag{14}$$

At this point, formulas (7)–(14) can be used to decompose and empirically analyze the carbon emission drivers in China.

3. Discussion

In this section, we attempt to discuss the results from an international perspective in two ways. In Section 3.1, we investigate China's contribution to and influence on global CO_2 emissions based on the analysis of total CO_2 emissions. While in Sections 3.2 and 3.3, we show real applications of the decomposition analysis in policy assessments using real cases from our analysis of China. As a reference, we first discuss relevant profiles from China, as shown in Fig. 2.

Fig. 2 summarizes the profile of China from 2005 to 2016. The population steadily increases at the rate of five million persons annually. Likewise, economic activity also steadily increases at the same rate. Notably, residential consumption expenditures steadily increase and become significant.

3.1. Total amount and intensity of carbon emissions in China

As discussed in the introduction, China is the largest energy consumer, so it is necessary to measure China's carbon emissions. Therefore, we calculate and analyze carbon emissions from energy consumption in China from 2005 to 2016 (based on the data in 2005). The carbon emission intensity is usually selected for the comparative analysis of carbon emissions between regions. Carbon emission intensity refers to CO_2 emissions per unit of GDP, and this indicator is mainly used to measure the relationship between a country's or region's

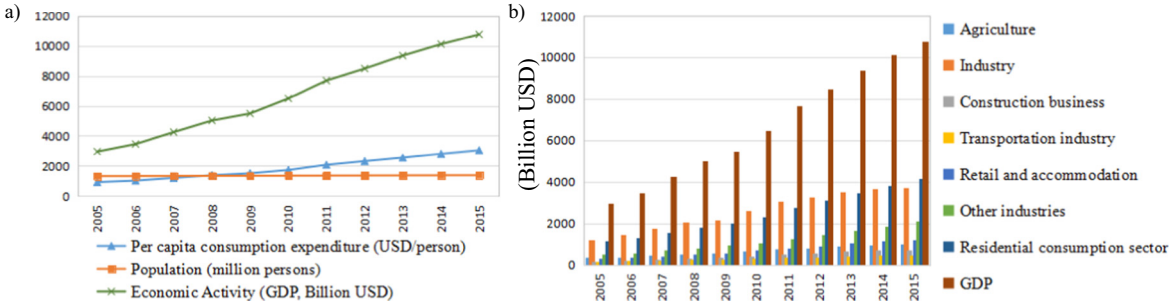

Fig. 2. Summary profile of China during 2005–2016.
*Data sources: *China Statistical Yearbook* (2005–2016).

economy and carbon emissions. If a country or region is experiencing economic growth, CO_2 emissions per unit of gross national product decreases, indicating that the country or region has achieved a low-carbon development model. Therefore, in this section, carbon emission intensity of China is also measured to comprehensively analyze and understand China's carbon emissions. The results of the decomposition analysis are shown in Fig. 3.

It can be seen from these results that China's energy consumption in 2005 was 4.93 billion tons, accounting for 16.72% of the total global carbon emissions. In 2015, the total amount of CO_2 produced from China's energy consumption reached 9.64 billion tons, accounting for 26.56% of the total global carbon emissions, which had a 10% increase from 2005, although the rate of increase in CO_2 emissions in China gradually decreased. By the end of 2015, carbon emissions per unit of GDP in China was 0.9 kg/USD, and the intensity of carbon emission decreased each year, with the greatest drop of 6.8%. However, the intensity of carbon emissions in China was still higher than that of the global average. This also shows that the GDP growth rate of China is lower than that of the total carbon emissions due to the slow growth of China's economic output in recent years, resulting in the persistence of a high carbon emission intensity and severe environmental pollution.

3.2. Kaya-LMDI decomposition model

In this section, we attempt to determine what the decomposition analysis results indicate about the emissions factors. Using the Kaya-LMDI decomposition model to decompose China's carbon emissions from energy consumption from 2005 to 2016, industrial energy structure effect, industrial energy intensity effect, industrial structure effect, economic output effect, population scale effect and gross effect can be obtained. Fig. 4 shows the results of carbon emissions decomposition. From 2005 to 2016, total effect of carbon emissions after decomposition is basically consistent with the trend of total carbon emissions from energy consumption in China, with an overall S-type increase. From 2005 to 2009, total growth rate of carbon emissions from energy consumption in China was relatively low, with an average of 6.4%. From 2009 to 2012, total amount of carbon emissions increased at the greatest rate, and the average growth rate reached its maximum13.4%, in this period. From 2012 to 2016, the growth rate gradually dropped to 5.1%. The results show that since the environmental protection targets of the "10th Five-Year Plan" (2001–2005) were not fully realized, in the early period of the "11th Five-Year Plan" (2006–2010), China's total carbon emissions increased rapidly. At the end of the "11th Five-Year Plan", the growth rate gradually decreased, but there were still some defects. During the "12th Five-Year Plan" (2011–2015) period, under low-carbon development, China controlled its energy consumption to a certain extent, restraining the CO_2 emissions and making progress in the control of atmospheric environmental pollution.

Further analysis of the decomposition results shows that these results are consistent with most studies of carbon emissions from energy consumption in China (e.g., Xu et al., 2012; Fan, 2013; Tian et al., 2015). These results show that, the contribution of energy structure effect and energy intensity effect to China's carbon emissions is negative, which greatly restraining the carbon emissions. The contribution of industrial structure effect on carbon emissions is first positive and then negative. The economic output effect and population scale effect on the increase in carbon emissions are positive. Total carbon emission effect is approximately proportional to the economic output effect. Thus, the main driving factor of China's increase in carbon emissions is the economic output effect.

From the analysis of energy structure effects, as shown in Fig. 5, the contribution of energy structure effect on China's carbon emissions from energy consumption is positive, and a change in the energy structure can promote CO_2 emissions to some extent. Fig. 8 also shows that due to the increase in CO_2 emissions from the change in industrial energy structure, energy structure effect from industry plays a major role

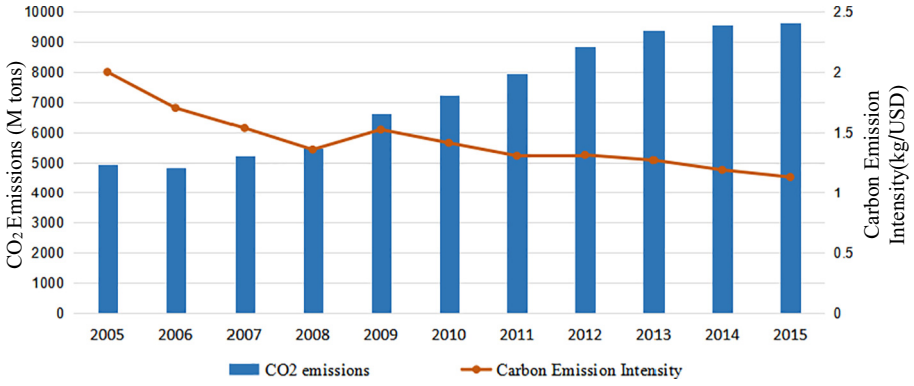

Fig. 3. Total carbon emissions from energy consumption in China during 2005–2016.
*Data sources: China Statistical Yearbook and China Energy Statistics Yearbook (2005–2016).

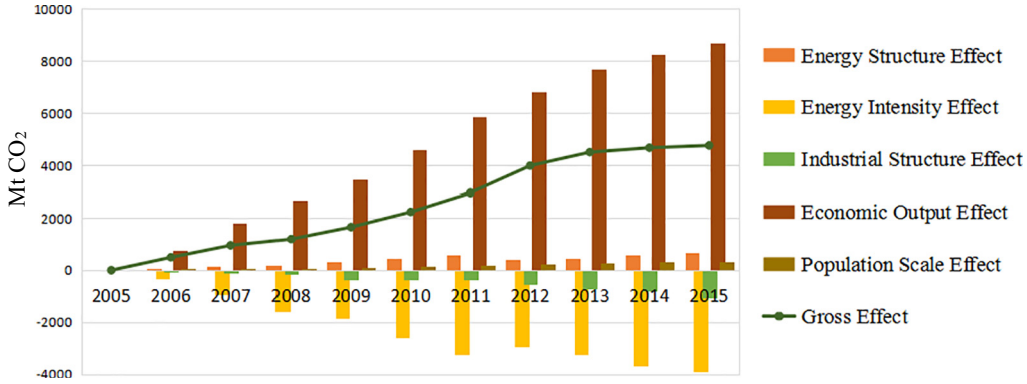

Fig. 4. Carbon emission accumulation effect in China from 2005 to 2016.
*Data sources: China Energy Statistics Yearbook (2005–2016).

in China's CO_2 emissions. The reason for this result is that energy consumption in industry mainly depends on raw coal, coke, etc. The industry consumption proportion closely follows the variation in the energy structure effect, which is also consistent with the result of the accumulation effect (Xu et al., 2012). On the other hand, agriculture plays a constraining role in CO_2 emissions, but the restraint intensity is far lower than that of the consumption intensity. Therefore, the energy structure effect still generally promotes CO_2 emissions.

In the analysis of energy intensity effects, as seen in Figs. 4 and 6, the contribution of energy structure effect on China's CO_2 emissions from energy consumption is negative, and the contribution of energy intensity effect has restrained China's carbon emissions significantly. Among the effects, energy intensity effects in the industrial and residential consumption sectors are the greatest, accounting for approximately 82% of the total energy intensity effect. The inhibition effect of transportation and tertiary industry continues to increase annually, whereas the inhibition effects of agriculture and construction are the weakest. Thus, from 2005 to 2016, the scale of economic output of China's industrial, transportation and tertiary industries expanded rapidly, the residential consumption increased gradually, and the economic output of agriculture and construction increased steadily. Energy intensity refers to the ratio of energy consumption to economic output. Therefore, the control of energy intensity requires increasing energy conservation and promotes energy-saving technologies. Low carbon development can be achieved by improving the efficiency of old and new energy uses.

In the analysis of industrial structure effects, from Fig. 7, we can see that the effect of the industrial structure on carbon emissions from China's energy consumption initially presents a positive influence, but then a negative one. From 2005 to 2013, the industrial sector has been playing a promoting role in the industrial structure effect, while other sectors have played a restraining role. During 2013 to 2016, the effect of the industrial sector changed from promoting to restraining with a strong inhibition effect. The construction industry played a role in promoting the effect, while the other 5 major sectors had restraining effects. Combined with Figs. 4 and 7, the contribution trend of the industrial sector to the industrial structure effect is the same as that of the industrial structure effect on carbon emissions, and the industrial sector plays a leading role in industrial structure effect. From 2005 to 2016, due to some policies, China further refined the industrial division of labor through industrial transformation and structural adjustments and showed a high level of industrial structure in terms of economic growth rate and proportion of total economic volume. That is, with increasing economic development, the energy structure effect on carbon emissions changed from promoting to restraining.

As shown in Fig. 4, from 2005 to 2016, the economic output effect was positive and increased annually, which contributed the most to the increase in carbon emissions from energy consumption in China. This conclusion is consistent with that of Fan (2013), who used LMDI-PDA decomposition method to study the driving factors of carbon emissions from energy consumption in China. During this period, China's total GDP grew 266%, and GDP per capita grew by 248% (at constant 2005 prices). According to the environmental Kuznets curve, when the level of economic development in a region is relatively low, the degree of environmental pollution is lower. But as the economy develops, the environmental pollution increases, and the level of environmental degradation will increase along with economic growth. After economic development reaches a “turning point”, further development of the economy results in a decline in environmental pollution from high to low levels. The extent of environmental pollution has gradually decreased, and environmental quality has gradually improved. In 2009 and 2014, there were two short-term declines in economic output effect and total effect in China, and these declines were mainly affected by the 2009 Copenhagen Climate Conference and the 2014 Asia Pacific Economic Cooperation (APEC) Summit, but an economic development inflection point did not occur. Therefore, the increase in CO_2 emissions is an inevitable result of China's economic development.

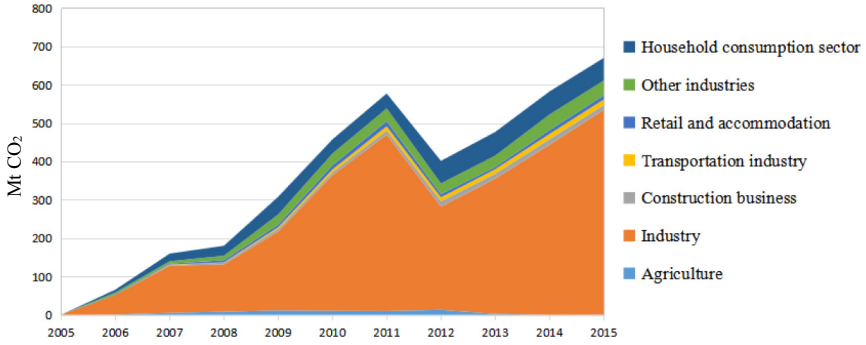

Fig. 5. Energy structure effect in China from 2005 to 2016.
*Data sources: China Energy Statistics Yearbook (2005–2016).

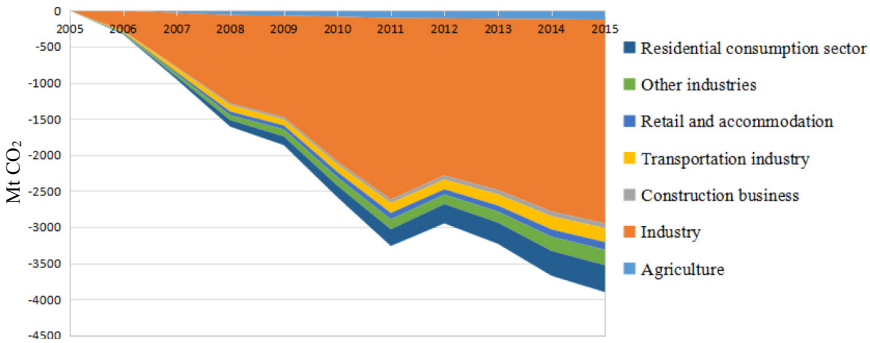

Fig. 6. Energy intensity effect in China from 2005 to 2016.
*Data sources: China Energy Statistics Yearbook (2005–2016).

Similarly, as seen in Fig. 4, from 2005 to 2016, the population scale effect has always contributed positively to the total carbon emissions in China. From 2005 to 2013, the rate of increase in the population scale effect and the gross effect increased simultaneously. In addition, from 2013 to 2015, these two effects also showed a decreasing trend, indicating that the increase in population in China led to an increase in carbon emissions. The reason for this finding may be that with the increase in population, the pace of urbanization in China accelerated, and urbanization, which includes increasing the size of cities, building water conservancy facilities, and constructing railways, has a greater impact on carbon emissions and leads to the rapid development of industry, construction, transportation and tertiary industries. Consequently, the corresponding increase in demand caused an increase in energy consumption, which in turn increased the total carbon emissions in China. This conclusion is similar to that of Fan (2013), who suggested that an increase in population contributes to an increase in carbon emissions.

3.3. Carbon emissions from energy consumption of various industries

In this section, we still discuss the carbon emissions of China's energy consumption into two categories: carbon emissions and intensity. However, what we analyze here is the carbon emissions from each industry.

3.3.1. Total amount of carbon emissions

Fig. 8 shows that from 2005 to 2006, carbon emissions of energy consumption in China's industrial sector, which is about 71%, accounted for the greatest proportion of total carbon emissions, and carbon emissions of agriculture, construction, transportation, retail and accommodation, other industries and the residential consumption sector, as percentages of the total emissions are 3%, 1%, 8%, 2%, 5%, and 10%, respectively. From 2015 to 2016, carbon emissions of agriculture, industry, construction, transportation, retail and accommodation, other industries and the residential consumption sector, as percentages of the total emissions are 2%, 68%, 1%, 8%, 3%, 7%, and 11%, respectively. The total amount of carbon emissions in these various sectors decreased by 1%, 3%, 0%, 0%, −1%, −2%, and −1%, respectively, compared to the corresponding emissions in 2005 to 2006.

Therefore, the main source of carbon emissions from energy consumption in China is still industry sector, and the contribution from the transportation and residential consumption sectors is also relatively high. Because of further economic transition, the proportion of energy consumption in the retail and accommodations sector has gradually increased, and the associated carbon emissions have also shown an increasing trend. This reflects the policy support and rapid development of tertiary industries in the period of the "11th Five-Year Plan" and the "12th Five-Year Plan". Adjusting the industrial energy structure and creating a low-carbon industrial system have gradually become important approaches for economic transformation and development mode adjustments.

3.3.2. Intensity of carbon emissions

Fig. 9 shows that from 2005 to 2016, the variations in carbon emission intensity of the industrial sector and transportation energy consumption in China show the same trend as that of the total carbon emission intensity. It is always higher than that of the total carbon emission intensity and decreases annually. The variation trends of carbon emission intensity in other sectors are relatively stable and have been kept between 0 and 1. The carbon emission intensity in the various sectors decreased by 52%, 38%, 51%, 28%, 40%, 39%, and 36% from 2005 to 2006 levels. In addition, China's total carbon emission intensity decreased by 43%.

The results show that carbon emission intensity of the industrial and transportation sectors is high in China; meanwhile, the fact that China's carbon emissions are mainly caused by industry, is also mentioned in the study of Xu et al. (2012). As an important branch of the three industries, the industrial and transportation sectors have low energy

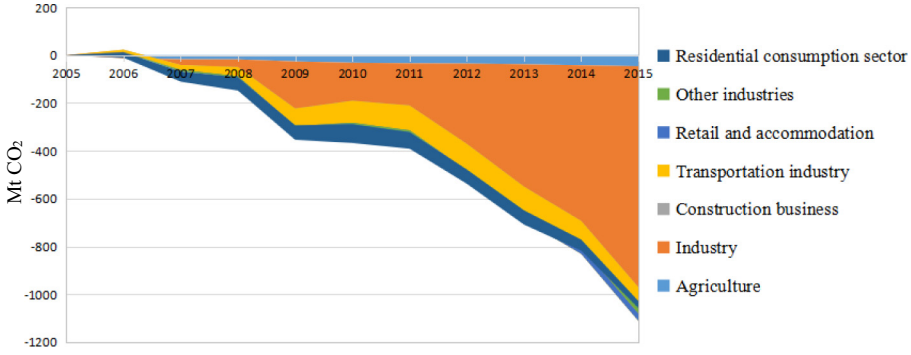

Fig. 7. Industrial structure effect in China from 2005 to 2016.
*Data sources: China Energy Statistics Yearbook (2005–2016).

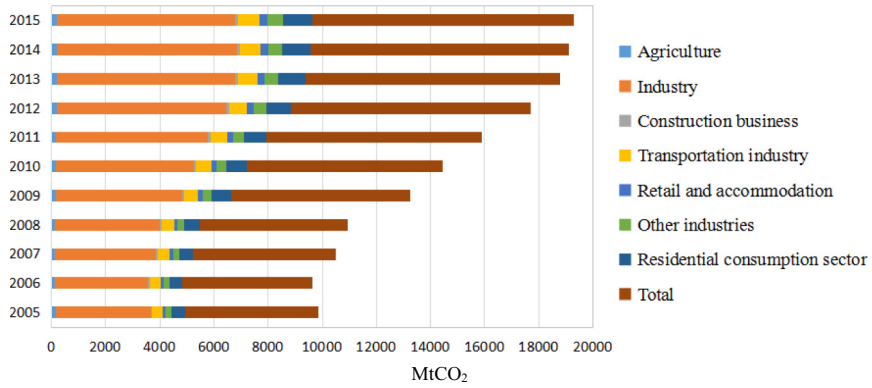

Fig. 8. Carbon emissions of energy consumption in various sectors from 2005 to 2016.
*Data sources: China Energy Statistics Yearbook (2005–2016).

efficiency, imperfect energy structure and high energy consumption. Therefore, the Chinese government needs to take effective measures to curb carbon emissions from energy consumption in secondary and tertiary industries by improving energy efficiency, researching clean energy, and promoting technological progress.

4. Conclusions

The present work quantifies the relative contributions of various factors and correlates them to the evolution of CO_2 emissions in China. These findings hopefully provide insight into other nations, especially developing countries and those engaged or becoming engaged in carbon emission reduction.

From the perspective of the decomposition effect, a decrease in energy intensity effect clearly promotes a decrease in carbon emission intensity of energy consumption in China, and energy structure and industrial structure effect promote a decrease in carbon emission intensity to a certain extent. Changes in economic output effect and population scale effect restrain the decrease in total carbon emissions. Therefore, in order to move towards a low-carbon energy system, energy intensity reduction is the key channel for high-energy-consuming countries to reduce CO_2 emissions.

From the perspective of economic development dependence, as mentioned in Section 3.2, the Chinese economy highly depends on energy consumption because of its status as a fast-growing economy. Thus, the increase in carbon emissions is basically promoted by aggressive economic output and increased energy consumption. Policy makers should consider the strategy of energy resource integration for the greatest improvement in environmental quality without affecting economic growth. According to the analysis, gas energy consumption is favorable for improving environmental quality because gas consumption generates less pollution than the use of other energy sources. However, natural gas reserves of China are limited, whereas coal reserves in China are considerable. Therefore, policy makers should promote the utilization of gas in industry and transportation sectors to minimize carbon emissions. Meanwhile, China should also introduce more advanced energy technologies, coalbed methane and gas-to-liquid technologies, as well as promote the renewable energy to reduce its dependence on fossil energy consumption.

From the perspective of energy consumption sector, China's CO_2 emissions from energy consumption mainly come from industry, and the consumption proportions of the residential consumption sector and transportation industry are also relatively high. Meanwhile, tertiary industry accounts for an increasing proportion of energy consumption. In the face of these challenges, it is necessary to strictly control carbon emissions and promote carbon capture in industrial areas and eliminate back capacity and overcapacity regulations. Meanwhile, the industrial structure layout should be adjusted: develop low-carbon agriculture, implement regulations stipulating without increase in fertilizer usage, improve water and fertilizer management, and control crop straw burning to reduce greenhouse gas emissions in agriculture. Additionally, strengthening of building energy conservation measures, implementation of a green building development plan, promotion of renewable energy in construction, construction of low-carbon transportation systems, acceleration of development of low-carbon logistics, and encouragement of the use of energy-saving, clean energy and new energy transportation tools should also be considered. Furthermore, promoting the transformation of the industry-led industrial structure to the tertiary industry-led industrial structure, advocating for the concept of low carbon, avoiding rapid growth in energy consumption and reducing

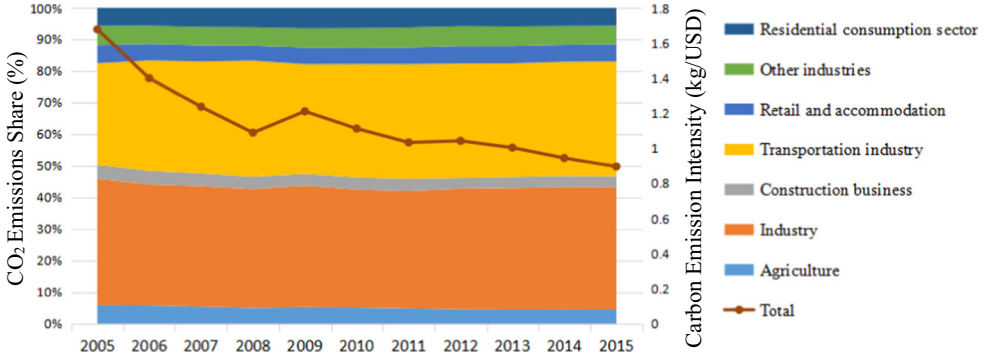

Fig. 9. Carbon intensity of each industry (sector) from 2005 to 2016.
*Data sources: China Energy Statistics Yearbook (2005–2016).

consumption of domestic energy must also be applied. Rational consumption and green consumption must be realized, the development mode must eventually transit to low-carbon economy development.

In view of the obvious differences in industries among regions, China should formulate various support policies to support low-carbon development in different regions and form low-carbon development models that are suitable for different regions. All regions should increase their financial support for low-carbon development, strengthen the use of the public-private-partnership (PPP) model, demonstrate the role of government guidance, improve their energy conservation, environmental protection, and low carbon consumption requirements, as well as other requirements of the government system, and promote the development of economy into a new stage of low-carbon development. At least in the short term, these changes can serve as a tool for reaching the CO_2 reduction target of a region/country and can contribute to the reduction of CO_2 emissions both in China and worldwide.

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Author contributions

Xiaojun Ma and Biying Dong provided the main ideas for the article, the methods used and the framework of the whole study; Changxin Wang was responsible for the overall construction of the article (text and graphics); Biying Dong was responsible for the consolidation of data and writing of the article content; Ruimin Chen was responsible for the model research; Guocui Gu and Yifan Li were responsible for the English content; Hongfei Zou was responsible for the collection of data; Wenfeng Zhang was responsible for the first part of the literature review; and Qiunan Li was responsible for collecting the related documents.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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